Intraslab Seismicity and Seismic Structure of the Northern Cascadia Subduction Zone

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Investigations Undertaken

This grant is to support work on the structure of the Cascadia subduction zone and its controls on earthquake hazard in the Pacific Northwest. It provides partial support and research funding for a postdoctoral fellow, research technician, and logistical costs of field operations. The work is based upon the analysis of three-component broadband seismograms located in southwestern British Columbia and northwestern Washington. Here we report on 1) the effect a hypothesized, serpentinized mantle forearc on ground motions from both thrust and intraplate events; and 2) preliminary investigations of forearc mantle structure in northern Cascadia.

Results

In the months after the original proposal submission for this project, I had occasion to discuss recent research results concerning subduction zone structure in southern Cascadia with Roy Hyndman of the Pacific Geoscience Centre. Our discussions have led to a new and compelling interpretation for seismic observations made across central Oregon, notably that the forearc mantle is highly hydrated and serpentinized (see Figure 1, and Bostock et al., 2002). This hypothesis has potentially important implications for our understanding of earthquake hazard in the Pacific Northwest through its effect on ground motions from thrust and intraslab seismicity, and its potential control on the rupture areas of both thrust and "silent slip" events (see Brocher et al. (2002) and abstracts to be presented at the *New Views of Seismic Hazards in Cascadia* session at the 2002 Fall AGU meeting). The implications of this feature on ground motions from local earthquakes, and its signature further north along strike in northwest Washington and southwest British Columbia are discussed below.

1. Ground motions from thrust and interplate events

Our efforts to model the effects of large-scale, subduction zone structure on ground motions in Cascadia are based in part on earlier work by Cohee et al (1991). These authors modelled ground motions in Oregon and Washington from a thrust earthquake using a crustal model from the LITHOPROBE-Southern Vancouver Island seismic reflection profile (Clowes et al., 1987), and a relatively simple mantle model comprising a dipping oceanic plate exibiting little down-dip variation. They found that the complex crustal structure had a rather minor effect on ground

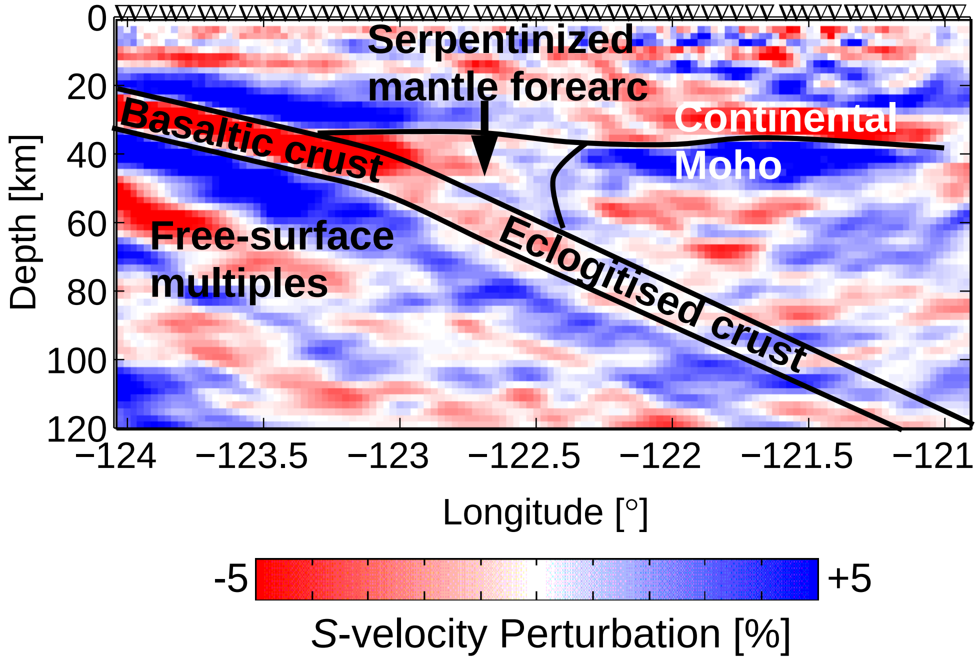

Figure 1: Interpretation of S-velocity perturbation image (Bostock et al., 2002) derived from scattered teleseismic waves recorded during the IRIS-PASSCAL CASC93 experiment (Nabelek et al., 1993).

motions; rather, peak amplitudes resulted from direct S and post-critical S-reflections off the oceanic Moho of the subducting plate. We have revisited this problem with the objective of understanding how the presence of serpentinized forearc mantle might modify the conclusions of this previous study, and to understand its effect on ground motions from intraplate sources. Wave propagation through two simple models of subduction zone structure has been simulated using 2-D pseudo-spectral synthetic seismograms. The *reference* model (figure 2, top panel) involves an oceanic plate comprising homogeneous oceanic crust and mantle, subducting beneath a homogeneous continental crust and mantle. The *perturbed* model (figure 2, lower panel), which is based on the interpretation of Bostock et al. (2002), employs two modifications. First, a lateral gradient in forearc mantle velocities is introduced from very low (V_s = 2500 m/s) at the wedge corner to ambient values (V_s = 4500 m/s) near at the arc. This feature is intended to represent the effect of hydration and serpentinization. The second modification involves a downdip increase in oceanic crustal velocities starting at a depth of 50 km that results in a disappearance of the oceanic crustal velocity contrast by 120 km depth. This structure is meant to represent the effect of eclogitization. We note, moreover that eclogitization is considered by many to be a primary cause of shallow intraplate seismicity, and, is also likely to be a major source of water for hydration of the overlying wedge.

In our modelling of thrust earthquakes, we considered point sources at the updip and downdip limits of the locked zone (Oleskevitch et al., 1999). The results are similar for both sources, and are broadly consistent with the modelling undertaken by Cohee et al. (1991). However, we find that ground motions at locations corresponding to major urban centers (ie Portland, Seattle, Vancouver) are influenced by post-critical reflections off the continental Moho in the *reference* model, but that post-critical reflections from the oceanic Moho are dominant in

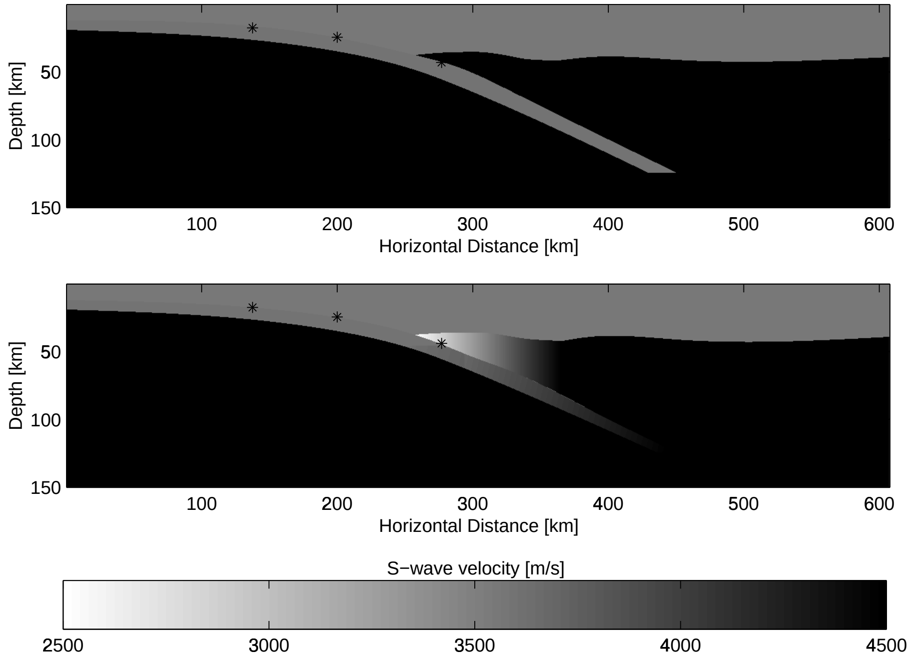

Figure 2: *Reference* (upper panel) and *perturbed* (lower panel) *S*-velocity models used in the simulation of ground motions from thrust and intra-slab earthquakes. Asterisks show locations of sources corresponding, from left to right, to the up- and down-dip limits of rupture, and an intraslab event, respectively

the *perturbed* model. This difference in response does not change peak amplitudes appreciably (see figure 3, left panel), but it does cause some rearrangement in the distance over which maxima occur. These observations are easily understood by noting that serpentinization has lowered mantle velocities to values below those of the continental crust, thereby permitting penetration of wide-angle signals to the next deepest interface exhibiting increased velocities, ie the oceanic Moho.

The effect of serpentinization is more dramatic in the case of an intra-plate source, which we have located at the top of the oceanic crust at a depth of $\sim$ 50 km. At depths below the continental Moho in the *reference* model, the oceanic crust acts as a waveguide for wide-angle propagation and much of the source energy is tunnelled downward along this structure. However, forearc serpentinization in the *perturbed* model creates a window that allows upward propagating energy to escape to the surface. This includes post critically reflected energy from the oceanic Moho which contributes to ground motions that are approximately 5 times higher those in the *reference* model at epicentral distances of $\sim$130 km from the source (see figure 3, right panel).

2. <u>Large-scale structure of the northern Cascadia subduction zone</u>

Installation of POLARIS-BC three-component broadband stations commenced in May 2002 and as of end of June 2002 a total of 15 stations were operating over the region of southwestern BC-NW Washington as shown by the labelled squares in figure 4. We consider data from a subset of these stations in the preliminary analysis shown below. The second phase of deployment has begun and will involve the installation of a further 15 stations by end of November 2002 (triangles in figure 4).

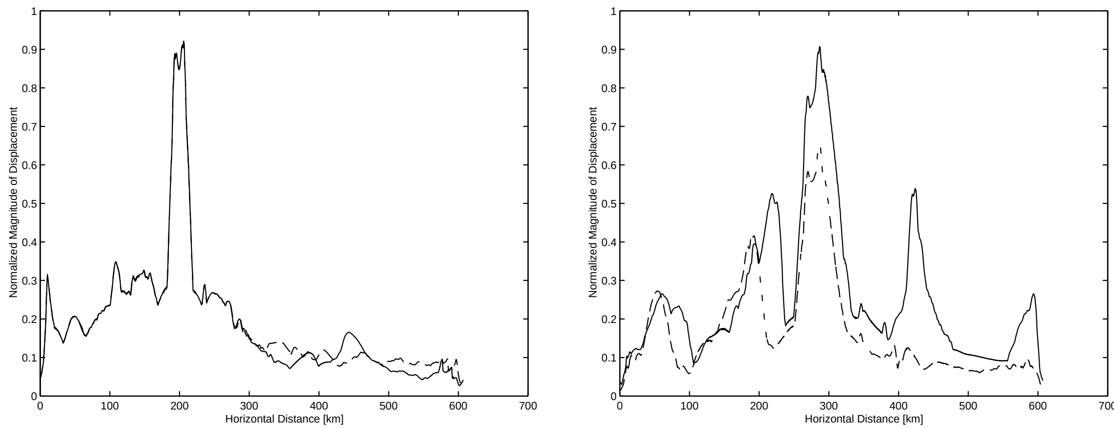

Figure 3: Effect of serpentenized mantle forearc on ground motions from thrust (left panel, source at 200 km horizontal distance on plate interface) and intraslab earthquakes (right panel, source at $\sim$ 300 km horizontal distance at top of oceanic crust). Maximum ground motions in *perturbed* and *reference* models are shown as solid and dashed lines, respectively.

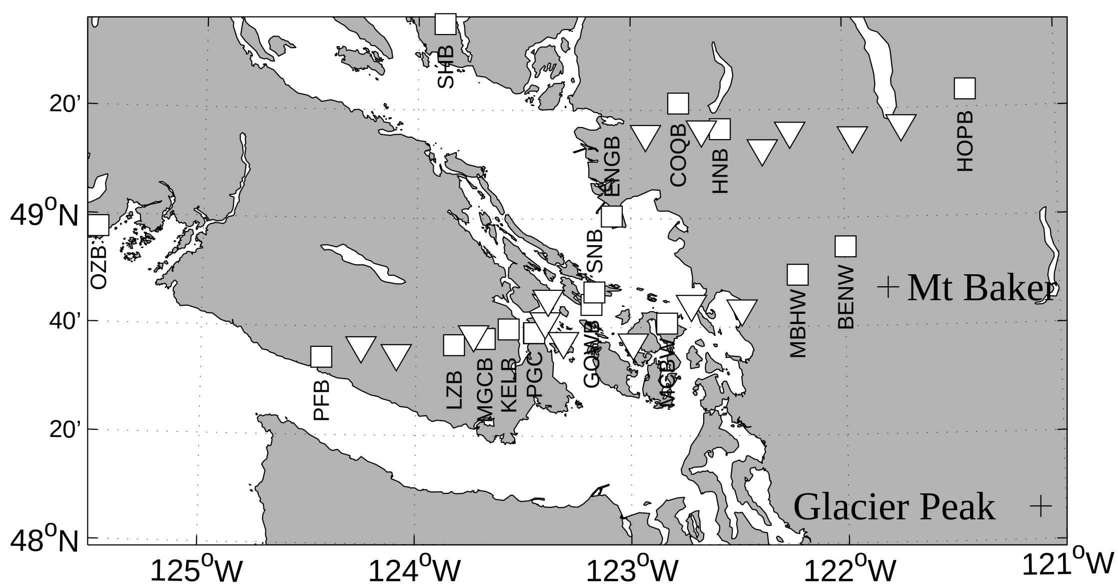

Figure 4: Map of current (labelled squares) and planned (unlabelled triangles, to be deployed by end of November 2002) broadband, three-component stations in southwestern British Columbia and Northwest Washington.

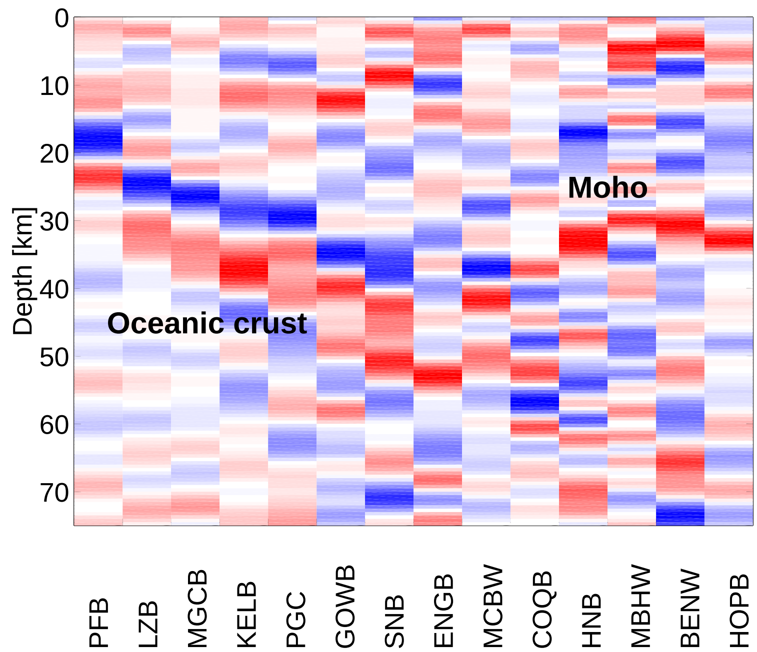

Figure 5: Preliminary receiver function profile determined from stations (ordered in longitude, west to east) shown in figure 4. Receiver functions have been low-pass filtered at 0.03 Hz and mapped from time to depth according to the traveltimes of backscattered S-waves from the free-surface P-reflection. Note that the signatures of the dipping oceanic crust at left and continental Moho at right are readily apparent.

We have assembled receiver functions from 14 stations which form an approximately linear array across southwestern B.C. and northwest Washington. An average of 6 events have been employed for each site, and the resulting receiver functions are mapped to depth using the kinematics for P-to-S back-scattering. This phase registered the strongest response on data from a comparable profile further to the south (Nabelek, 1993; Rondenay et al., 2001) A profile of the receiver functions is shown in figure 5 and although, the spacing of stations is irregular (see figure 4), the two main structural features identified by Nabelek et al. (1993) in central Oregon are clearly evident. The double lobed arrival evident over the western portion of the profile that dips to the east is the signature of the subducting oceanic crust. The continental Moho is evident on the eastern portion of the profile to station MBHW as a single pulse (red) arrival. Signatures of both of these features diminish as the Gulf/San Juan Islands region is approached, a behaviour that may manifest the effects of serpentinization and eclogitization. The clarity of the observed response acquired using only a small number of data, 1-D analysis and irregular sampling, is encouraging. With the deployment of a further 13 stations by November 2002, a regular ($\sim$ 15 km) sampling along the southern line will be achieved and allow us to begin a more formal 2-D analysis of structure along the profile.

Non-technical Summary

In this report, we have presented preliminary results from studies of earthquake hazard and subduction zone structure in the Pacific Northwest. Ground motions from intra-slab earthquakes are shown to be, locally, up to 5 times greater in the presence of a serpentinized mantle wedge than in its absence. The effect for thrust events is less significant. Preliminary analysis of receiver functions in northern Cascadia reveals clear signals from the subducting plate and continental Moho. In future work, we shall investigate the relation of these structures and possible forearc serpentinization to intraslab seismicity in northwestern Washington and southwestern British Columbia.

Data Availability

Data from POLARIS stations in British Columbia are available in SEED format and can be acquired through the AutoDRM of the Canadian National Earthquake Hazards Program (contact Jim Lyons at `lyons@seismo.nrcan.gc.ca` for further information). SEED data from stations in Washington state are available via personal request from the author at `bostock@geop.ubc.ca`.

References

Bostock, M.G., Hyndman, R.D., Rondenay, S., Peacock S.M. An inverted continental Moho and the serpentinization of the forearc mantle, *Nature*, **417**, 536-538, 2002.

Brocher, T.M., Parsons, T., Trehu, A.M., Crosson, R.S., Snelson, C.M., and Fisher, M.A. Seismic evidence for widespread serpentinized forearc upper mantle along the Cascadia margin, submitted to *Geology*, 2002.

Clowes, R.M., Brandon, M.T., Green, A.G., Yorath, C.J., Brown, A.S., Kanasewich, E.R., Spencer, C. LITHOPROBE-southern Vancouver Island: Cenozoic subduction complex imaged by deep seismic reflection, *Can. J. Earth Sci.*, **24**, 31-51, 1987.

Cohee, B.P., Somerville, P.G., Abrahamson, N.A. Simulated ground motions for hypothesized $M_w = 8$ subduction earthquakes in Washington and Oregon, *Bull. Seis. Soc. Amer.*, **81**, 28-56, 1991.

Oleskevich, D.A., Hyndman, R.D., Wang, K. The updip and downdip limits to great subduction earthquakes: Thermal and structural models of Cascadia, south Alaska, SW Japan and Chile, *J. Geophys. Res.*, **104**, 14965-14991, 1999.

Nabelek, J.L. et al. A high-reolution image of the Cascadia subduction zone from teleseismic converted phases recorded by a broadband seismic array, *Trans. Am. Geophys. Union*, **74**, 431 1993.

Rondenay, S., Bostock, M.G., Shragge, J. Multiparameter two-dimensional inversion of scattered teleseismic body waves, 3. Application to the Cascadia 1993 data set, *J. Geophys. Res.*, **106**, 30795-30807, 2001.